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Radio emission from early-type galaxies and cosmic microwave background experiments

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ABSTRACT

We investigate the possible contribution from the emission of accretion flows around supermassive black holes in early-type galaxies to current measurements of the cosmic microwave background (CMB) at radio frequencies. We consider a range of luminosities suggested by targeted radio observations and accretion models, and compute the residual contribution of these sources to the spectrum and bispectrum of the observed CMB maps. As for high-resolution CMB experiments, we find that the unresolved component of these sources could make up to ∼40–50 per cent of the observed Cosmic Background Imager (CBI) and Berkeley Illinois Maryland Association (BIMA) array power spectrum at $l > 2000$. As a consequence, the inferred $\sigma_8^{\rm SZ}$ value could be biased high by up to 6–7 per cent. As for all-sky experiments, we find that the contribution of accretion-flow sources to the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) bispectrum is at the 2–3 per cent level at most. At the flux limit that *Planck* will achieve, however, these sources may contribute up to 15 per cent of the bispectrum in the 60–100 GHz frequency range. Moreover, *Planck* should detect hundreds of these sources in the 30–300 GHz frequency window. These detections, possibly coupled with galaxy type confirmation from optical surveys, will allow number counts to put tighter constraints on the radio luminosity and accretion-flow properties of early-type galaxies. These sources may also contribute up to the 30 per cent level to the residual radio sources power spectrum in future high-resolution Sunyaev–Zeldovich (SZ) surveys (like the Atacama Cosmology Telescope or the Atacama Pathfinder Experiment) reaching mJy flux limits.

Key words: accretion, accretion discs – galaxies: elliptical and lenticular, cD – galaxies: nuclei – cosmic microwave background – infrared: galaxies.

1 INTRODUCTION

Cosmic microwave background (CMB) experiments have been able to measure cosmological parameters to an unprecedented level of accuracy (Spergel et al. 2003). For this to be possible, however, the contribution to the primary signals must be disentangled from other astrophysical emissions at the observed frequencies. Therefore, foreground identification and removal is fundamental.

One of the major sources of contamination at small scales is constituted by point sources, and several studies have been carried out to estimate their contribution to CMB anisotropy experiments (Toffolatti et al. 1998; Argüeso, González-Nuevo & Toffolatti 2003; White & Majumdar 2004). Generally, source counts are determined in the radio band, through deep Very Large Array (VLA) surveys down to μJy levels at 1.41, 4.86 and 8.44 GHz. These counts are then extrapolated to the higher range of frequencies relevant for CMB experiments (Gawiser & Smoot 1997; Toffolatti et al. 1998, 1999; De Zotti et al. 2000). This extrapolation provides a reasonable estimate of the contribution from the 'steep' and 'flat' spectrum sources (with $F_\nu \propto \nu^{-\alpha}$ and $\alpha \geqslant 0$, such as compact radio galaxies and radio loud quasars), but it strongly under-represents an important contribution from a class of sources with inverted spectra ($\alpha < 0$; e.g. De Zotti et al. 2000).

Inverted-spectrum sources, such as GHz peaked sources (GPS; O'Dea 1998; Guerra, Haarsma & Partridge 1998), are bright (flux ∼1–10 Jy) and rare, and are generally associated with bright active galaxies or quasars at high redshifts. Their contribution to the CMB experiments was studied by De Zotti et al. (2000). These sources, being bright and rare, are easily identified in the CMB maps and removed.

There is, however, another class of inverted-spectrum sources, much fainter (flux ∼1 mJy) but much more common, associated

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with emission from the nuclei of nearby galaxies. Radio continuum surveys (at $\nu < 8$ GHz) of elliptical and S0 galaxies have shown that the sources in radio-quiet galaxies tend to be extended but with a compact component with relatively flat or slowly rising radio spectra. Recent VLA studies at high radio frequencies (up to 43 GHz), although carried out only on a limited sample of objects, have shown that all of the observed compact cores have spectra rising up to ∼20–30 GHz. These sources of radio emission are believed to result from the process of accretion of gas into the supermassive black holes (BHs) likely ubiquitous in the centres of galaxies (Magorrian et al. 1998).

A popular model to describe the broad-band spectral energy distribution from the accretion flows around these supermassive BHs is the advection-dominated accretion flow (ADAF) model (Rees et al. 1982; Narayan & Yi 1994). Within the context of this model, the foreground contribution to the CMB experiments, and in particular to *Planck*, was studied by Perna & Di Matteo (2000). In particular, they estimated the contribution of these sources both within the 'standard' ADAF model, where the accretion rate is independent of the radius R of the flow [implying that all the mass is accreted into the BH], and within the context of the ADAF model with winds, where not all the mass is accreted by the BH, but some is lost into winds (Narayan & Yi 1995a; Blandford & Begelman 1999). In this case, the radio emission is suppressed because winds remove mass from the inner regions of the flow, where the synchrotron radiation giving rise to the radio emission is produced. Detailed modelling has only been possible for a handful of sources so far, as it requires multiwavelength, high-resolution data. Observations have yielded somewhat mixed evidence: in some cases, the emission is consistent with ADAFs with winds (i.e. suppressed radio emission; Di Matteo et al. 2000), whereas in others it is higher than the standard model with no wind (Di Matteo et al. 2001), probably because of extra power output by jets associated with the accretion flow.

Although studies of this class of sources of radio emission so far have been limited by low number statistics, Perna & Di Matteo (2000) showed that CMB experiments with the future *Planck* mission can provide interesting constraints from a statistical point of view. At the same time, these sources can be an important contaminant to CMB maps.

In this paper, we compute the contribution of the emission from accretion flows in early-type galaxies to the current signal of the Cosmic Background Imager (CBI), the Berkeley Illinois Maryland Association (BIMA) array, *Wilkinson Microwave Anisotropy Probe* (*WMAP*). We show that the signal from these unresolved sources is able to influence current limits on the power spectrum normalization σ_8. Finally, we make predictions on the power spectrum from residual sources in future high-resolution CMB experiments and on the bispectrum in all-sky experiments like *Planck* and *WMAP*.

2 MICROWAVE EMISSION FROM ACCRETION FLOWS IN ELLIPTICAL GALAXIES

As discussed above, there is evidence for the existence of supermassive massive BHs at the centre of galaxies. Inferred BH masses appear to be proportional to the mass of the bulge component of their host galaxies. Therefore, central BH masses are expected to be much larger in elliptical than in spiral galaxies. Independently of the details of the model for the production of the radio/microwave emission, this radiation is expected to be some fraction of the accretion energy, which is proportional to the mass of the BH. Therefore the contribution from the nuclei of the ellipticals is expected to dominate that from the nuclei of the spirals, which we neglect here. Similarly, among the population of ellipticals, the main contribution derives from the most massive galaxies. To make a conservative estimate of the emission from these galaxies, we consider only the bright end of the distribution, with $L \gtrsim L_*$. Studying a sample of nearly 9000 ellipticals in the Sloan Digital Sky Survey (SDSS), Bernardi et al. (2003) estimated a comoving number density $\Phi_* = (5.8 \pm 0.3) \times 10^{-3}\, h^3$ Mpc^{-3}. The redshift evolution of their sample appeared consistent with the law $\Phi_*(z) = 10^{0.4Pz}\Phi_*(0)(P \approx -2)$, found by Lin et al. (1999) in their sample of galaxies drawn from the Canadian Network for Observational Cosmology Field Galaxy Redshift Survey.

For a cosmological population of sources with intrinsic luminosity function $f(L_\nu)$ and redshift evolution $\Phi_*(z)$, the differential number counts are given by

$$\frac{\mathrm{d}n(S_\nu)}{\mathrm{d}S_\nu} = \int_0^\infty \mathrm{d}L_\nu \left[f(L_\nu)\Phi(z)\, \frac{\mathrm{d}V(z)}{\mathrm{d}z} \left| \frac{\mathrm{d}z}{\mathrm{d}S_\nu}(z, L_\nu) \right| \right]_{z(S_\nu, L_\nu)}, \tag{1}$$

where $\mathrm{d}V(z)/\mathrm{d}z$ is the comoving volume. In a flat cosmology with a cosmological constant, it is given by

$$\frac{\mathrm{d}V(z)}{\mathrm{d}z} = 4\pi D^2(z)\frac{\mathrm{d}D(z)}{\mathrm{d}z}, \tag{2}$$

where $D(z)$ is the comoving distance,

$$D(z) = \frac{c}{H_0}\int_0^z \frac{\mathrm{d}z'}{\sqrt{(1+\Omega_\mathrm{m}z')(1+z')^2 - \Omega_\Lambda(2z'+z'^2)}}. \tag{3}$$

We assume a cosmological model with $\Omega_\mathrm{m} = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 71$ km s^{-1} Mpc^{-1} (Spergel et al. 2003). In equation (1), $z(S_\nu, L_\nu)$ is derived by inverting the relation $S_{\nu(1+z)} = L_\nu(1+z)/[4\pi D_L^2(z)]$, where $D_L(z)$ is the luminosity distance.

We will consider two models for the emission from accretion flows in early-type galaxies (see Fig. 1); while these are computed

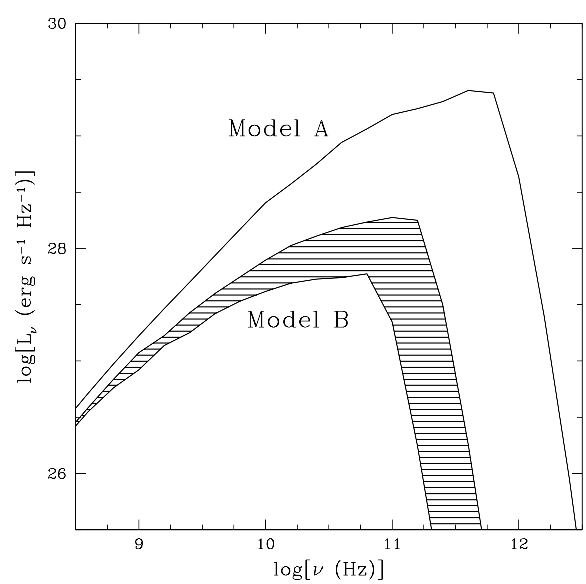

Figure 1. Synchrotron emission from low-radiative-efficiency accretion flows. The uppermost curve is the standard ADAF model with no outflows, with the shaded region in between the two lower curves representing a range of ADAF models with large outflows. The luminosity function in our Model A is a log-Gaussian with mean given by that curve. In the range of frequencies 30–100 GHz that we are mostly interested in here, the average luminosity in the shaded region is $\sim 10^{28}$ erg s^{-1} Hz^{-1}. Our Model B is described by a log-Gaussian with mean luminosity given by this value.

on the basis of a specific accretion model, they can be considered generally representative of the typical range in luminosity and spectral shape that characterize these sources. However, we should emphasize that, given the small sample of observations so far, and the uncertainties in the specific model parameters discussed below, our conclusions should be taken as indicative rather than general and final. Tighter constraints (which will leave less space for parameter variations) will be obtained with future, more sensitive CMB experiments together with a detailed, individual study of a larger sample of sources.

(a) *Model A*. This is the standard ADAF model (Narayan & Yi 1994), where the accretion rate is a constant function of the radius within the flow. In this model, the radio/microwave emission is due to synchrotron emission from the inner regions of the accretion flow. The emission at the self-absorbed synchrotron peak scales as $L_\nu \propto \nu_c^2 T$, where $\nu_c \propto T^2 B \propto T^2 \dot{M}^{1/2} M_{\rm BH}^{1/4} R^{-5/4}$ (Narayan & Yi 1995a); T is the electron temperature and B is the magnetic field strength. The ADAF model depends on a number of microphysical parameters (e.g. the flow viscosity, the ratio of gas to magnetic pressure, the adiabatic index of the fluid, the fraction of turbulent energy which goes into heating the electrons) in addition to geometrical parameters (e.g. the radial extent of the flow, the possible transition from a hot state to a cool disc at some radius), as well as on the BH mass $M_{\rm BH}$ and the accretion rate $\dot{M}$. Whereas some constraints on these parameters can be derived by multiwavelength observations and broad-band modelling of a given source, they cannot be well constrained a priori and they can in principle vary from source to source. Therefore, in a statistical study like ours, we can only adopt 'typical' values for all these parameters. In particular, we use the ones adopted by Di Matteo et al. (2000) for a BH of mass $\sim 10^9\ {\rm M}_\odot$ (as typical of the bright end of the galaxy luminosity function that we are considering here) and for an accretion rate ∼0.005 in Eddington units [note that the transition to an ADAF is believed (Narayan & Yi 1995b) to occur at rates below $\sim\alpha^2 \dot{M}_{\rm Edd}$, with α being the viscosity parameter of the flow]. The luminosity predicted by this model is shown by the upper line in Fig. 1. To allow for a spread in BH masses, accretion rates and parameters of the flow around this typical value, we take the luminosity function $f(L_\nu)$ to be a log-Gaussian with mean given by the curve displayed in the figure, and a standard deviation σ. We adopt $\sigma = 0.25$; the predicted number counts are very little dependent on the precise value of σ.

(b) *Model B*. The luminosity function for this model is calibrated on the sample of those sources for which the broad-band energy distribution was best fitted with an ADAF model with winds (Di Matteo et al. 2000). At frequencies in the range ∼30–100 GHz, the mean luminosity is roughly constant, and on the order of $L_\nu \sim 10^{28}$ erg s^{-1} Hz^{-1} (see the shaded region in Fig. 1 which encompasses the range of those observations). Hence, for this model we assume the mean luminosity to be constant over the considered frequency range and take the luminosity function $f(L_\nu)$ to be a log-Gaussian with mean given by the above value, and a standard deviation $\sigma = 0.25$.

Fig. 2 shows the number counts predicted by the sources in Models A and B. These sources are typically fainter than the radio sources presented in Toffolatti et al. (1998), and therefore the number counts are dominated by the local population. As a consequence, the slope in Fig. 2 is very close to Euclidean down to low flux levels. Being faint, these sources are not likely to be individually detected. However, because of the steepness of their number counts, they may contribute significantly to the residual signal in CMB experiments, where their relevance with respect to the Toffolatti et al. (1998) type of sources becomes increasingly important as the detection flux limit of the survey is reduced. Moreover, because the radio spectrum of these sources is inverted, they are less likely to be found at low frequencies, where most point-source catalogues are compiled, and therefore may be neglected in present data analysis. In the following, we will estimate the contribution of these accretion-flow sources to current CMB experiments, and explore the consequences that the emission from these (mostly unresolved) point sources can have on the determination of the matter power spectrum normalization σ_8 from these experiments.

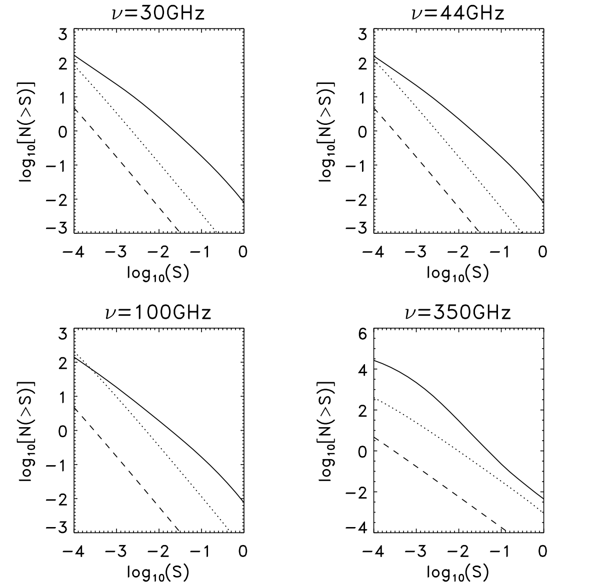

Figure 2. The number counts of accretion-flow sources at different frequencies. Short-dashed (long-dashed) lines correspond to Model A (B), as described in the text. The solid lines show radio and infrared sources as reported from Toffolatti et al. (1998), rescaled by a factor of 0.8 (Argüeso et al. 2003). Fluxes are in Jy and number counts are in deg^{-2}.

3 POINT SOURCES AND CMB EXPERIMENTS

Point sources are detected in CMB maps as high point-like fluctuations above the mean. Their detection depends on instrumental properties such as the beamsize and the noise level, as well as on the characteristics of the competing sky signals. Assuming that all sources above a given flux limit $S_{\rm lim}$ are subtracted from the data, residual sources still contribute to the statistics of the map (Pierpaoli 2003). For Poisson-distributed sources, the residual power spectrum and bispectrum are constant for all scales and read

$$\sigma^2(\nu) = C_l(\nu) = g(x)^2 \int_0^{S_{\rm lim}} {\rm d}S\, \frac{{\rm d}n}{{\rm d}S}\, S^2, \tag{4}$$

$$\tilde{b}(\nu) = g(x)^3 \int_0^{S_{\rm lim}} {\rm d}S\, \frac{{\rm d}n}{{\rm d}S}\, S^3, \tag{5}$$

where

$g(x) = 2(hc)^2/(kT)^3\, [\sinh(x/2)/x^2]^2,$

with $(hc)^2/(kT)^3 = 0.02\ \mu$ K sr Jy^{-1} and $x = \nu$ (GHz)/56.78.

The bispectrum is sometimes quoted as the dimensionless quantity $b \equiv \tilde{b}/T^3$. If the sources are clustered, the power spectrum is increased by

$$C_l(\nu)_{\rm clu} = w_l\, [I(\nu)]^2 \tag{6}$$

where the intensity

$$I(\nu) = g(x) \int_0^{S_{\rm lim}} {\rm d}S \, \frac{{\rm d}n}{{\rm d}S} \, S$$

and the w_l are the Legendre expansion coefficients of the angular correlation function:

$$w(\theta) = \sum_l \frac{1}{4\pi}(2l + 1)\, P_l(\cos\theta). \tag{7}$$

In order to compute the clustering term, we use the recent determination of the SDSS red-sample angular correlation function (Budavári et al. 2003). This estimate should provide a conservative limit to the clustering contribution, since the red sample contains more galaxies than just ellipticals, and ellipticals are more clustered than other sources.

Finally, given a particular experiment, it is useful to quote the (non-clustered) power spectrum as the *noise per pixel* caused by the residual point sources as

$$\sigma_b = \left(C_l / \theta_b^2\right)^{1/2}, \tag{8}$$

where θ is the pixel dimension, typically assumed to be the full width at half-maximum (FWHM) of the beam.

In the following, we will estimate the contribution of these sources to the current *WMAP*, CBI and BIMA signals.

The *WMAP* spectrum is clearly dominated by the primary CMB and, given the high flux cut ($\simeq$1 Jy), the observed bispectrum is likely to be dominated by other radio sources more luminous than elliptical galaxies at these frequencies. *WMAP*, however, presents the advantage of being an all-sky survey. Number counts of point sources which are confirmed to be elliptical galaxies by mean of other (optical and infrared) observations may hint about the typical radio emission of early-type galaxies.

CBI and BIMA, on the contrary, observed a small area of sky with high resolution and high sensitivity. These experiments detected the CMB power spectrum at very high values of l, where the primary CMB is weak and the point source contribution may be dominant. Therefore, the contribution of the emission from accretion flows in early-type galaxies may be significant to the observed CBI and BIMA power spectrum. We will estimate the importance of this contribution and its consequences on the derived cosmological parameter estimation.

3.1 *WMAP* detected sources

The *WMAP* experiment (Bennett et al. 2003) detected 208 point sources with a flux $S > 0.75$ in the V band. Among those sources, 29 have been identified as galaxies, whereas five have no identification and could therefore be galaxies (Trushkin 2003). Hence at most there is a total of 34 sources which are candidates for harbouring a source of emission from an accretion flow. This classification, however, does not distinguish elliptical galaxies from spirals. In order to determine how many of the *WMAP* sources could be elliptical-emitting according to the model described here, we proceeded as follows. We selected the sources in Trushkin (2003) according to the following two criteria: (i) we eliminated sources with measured redshift greater than $z \sim 0.01$, because if they were ellipticals emitting according to our models they would have an observed flux lower than 1 Jy; and (ii) we kept only sources with flat or inverted spectra. We then visually inspected the remaining sources in the Two Micron All Sky Survey (2MASS) data base, in order to select those which appear to be elliptical galaxies. We only found two sources of this kind. A comparison with the SDSS data (which currently covers about 10 per cent of the sky) finds only one elliptical galaxy among the *WMAP* sources. A total number of 2–3 ellipticals in the *WMAP* sample of detected sources seems a conservative estimate.

Model A predicts about 4.5 (8) sources above a flux $S_{\rm lim} = 1(0.75)$ Jy at 44 GHz, whereas Model B would predict 0.15 (0.25) sources for the same flux cut. These predictions seem to favour Model A, Model B predictions being 4–6σ away from observations. Current data therefore appears to suggest that the bulk of the elliptical galaxy population emits at $\sim$40 GHz more than the $\sim 10^{28}$ erg s^{-1} Hz^{-1} level assumed in Model B.

Planck should reduce the source detection threshold of at least one order of magnitude with respect to *WMAP*, possibly allowing for the detections of hundreds of these sources. Moreover, SDSS at completion should observe about one quarter of the sky. By comparing these two data sets, it will be possible to infer more conclusive statements on accretion models purely by means of radio number counts.

3.2 Current limits from CBI and BIMA

Recent results from high-resolution CMB experiments around 30 GHz like CBI and BIMA have shown a rise in the high l's of the CMB power spectrum which is interpreted as signature of the Sunyaev–Zeldovich (SZ) effect from galaxy clusters (Komatsu & Seljak 2002; Bond et al. 2002). This interpretation allows to infer a value of the matter power spectrum $\sigma_8 \simeq 1$ (Readhead et al. 2004). Residual radio point sources, however, are also likely to contribute to the observed power spectrum. We argue here that accretion-flow sources may present a sizable contribution to the CBI and BIMA power spectra.

In the CBI and BIMA cases, individual point sources have been subtracted from the data when identified by means of other observations of the same sky area at much lower frequencies.

In the CBI case, point sources above the flux limit of 3.4 mJy in the NRAO VLA Sky Survey (NVSS) at 1.4 GHz have been subtracted from the data. A residual point source signal, compatible with the observed point source population above the flux cut, has been modelled in the data analysis. The population of sources considered in our work, however, is not likely to be well represented by the detected one, because our sources are typically very faint at such low frequencies. As a result, the observed population may be rather biased toward flat or falling spectra sources. The observed population, in fact, shows a less steep dn/ds ($\propto S^{-1.875}$) than the one appropriate for the point sources considered here ($\propto S^{-2.5}$), and a mean spectral index $\alpha \simeq 0.45$, whereas our sources have $-0.8 \leqslant \alpha \leqslant -0.5$ in the relevant frequency range of $\sim$1–10 GHz. We extrapolate the NVSS flux limit to 30 GHz using a conservative spectral index $\alpha = -0.5$, and obtain for CBI $S_{\rm lim,30\,GHz} = 16$ mJy as a nominal flux limit for our sources.

In the case of BIMA, sources are detected with the VLA at 4.8 GHz with a flux limit of 150–175 μJy (Dawson et al. 2002). If radio sources have a flat or falling spectrum, then this procedure ensures the subtraction of sources at 30 GHz down to a very low flux limit. For this reason, the BIMA data analysis did not consider a possible contribution from residual point sources.

Because accretion-flow sources present an inverted spectrum, we do expect a residual signal from them below the flux limit at 30 GHz. Considering the conservative case of a spectral index of 0.5, such limit is $S_{\rm lim,30\,GHz} = 0.4$ mJy.

Given the considerations above, we assumed that all sources above the mentioned flux limits at 30 GHz have been subtracted from CBI and BIMA data, but the residual signal has not been taken into account. We computed the power spectrum from residual point

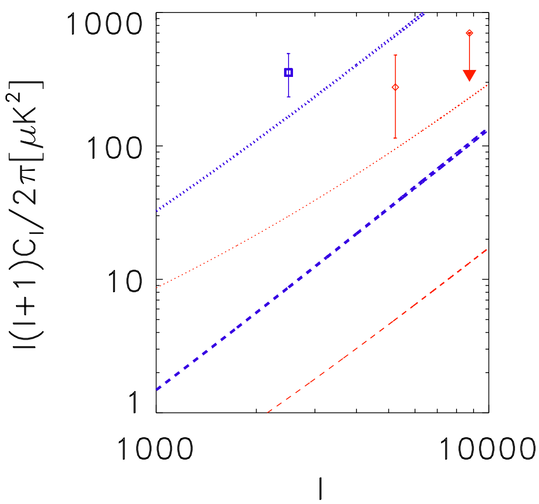

Figure 3. The residual power spectrum at 30 GHz from accretion-flow sources and the high-l points from the CBI and BIMA experiments. Thick/blue (thin/red) lines are relative to the CBI (BIMA) flux cut; the square/blue (triangular/red) points are the CBI (BIMA) results with 1σ error bars. The $l \simeq 9000$ BIMA point is a 90 per cent upper limit. Dotted (dashed) lines refer to Model A (B), as in Fig. 1.

sources given the above mentioned flux limits (relative to the two experiments) and the two different models. We also took into account the sources correlation which contribute about 15–20 per cent. We then compared the residual power spectra with the CBI band power for $l > 2000$ and the BIMA ones at $l > 5000$. Our results are presented in Fig. 3. We find that, in the case of the emission at the level of Model B for all sources, their contribution would be 2.4 per cent for CBI and 2.5 per cent for BIMA, whereas in the case of Model A the contribution would be 47 per cent for CBI and 46 per cent for BIMA. Because $C_l^{\mathrm{SZ}} \propto \sigma_8^7$, in the latter case the unresolved signal from these sources could produce a bias of 6–7 per cent in the current determination of σ_8 with this method (Komatsu & Seljak 2002). The real value of σ_8 is still a very controversial issue, but the one inferred from SZ power spectrum is certainly in the high end of the considered range. A lower σ_8 value would be in better agreement with determinations from cluster abundance (Pierpaoli 2003), the *WMAP* results (Spergel et al. 2003) and some weak lensing experiments (Heymans et al. 2004).

3.3 Residual signal in all-sky experiments

In this section, we discuss the residual contribution from accretion-flow sources to the bispectrum of *WMAP* and *Planck*.

In Table 1 we report the bispectrum produced by residual sources for different flux cuts and normalizations, compared with the one implied by more standard radio and infrared (IR) population as in the model by Toffolatti et al. (1998) (see also Argüeso et al. 2003).[1] *WMAP* measured the bispectrum in Q (40 GHz) and V (61 GHz) bands, and found $\tilde{b} = (9.5 \pm 4.4) \times 10^{-5}$ and $(1.1 \pm 1.6) \times 10^{-5}$ μ K^3 sr^2, respectively. For a nominal flux cut at $S_{\mathrm{lim}} = 0.75$, accretion-flow sources would imply that $\tilde{b} = 2.9 \times 10^{-7} (1.1 \times 10^{-8})$ μK^3 sr^2 in the V band for Model A (B) and $\tilde{b} = 1.7 \times 10^{-6} (6.0 \times 10^{-8})$ μK^3 sr^2 in the Q band, so they contribute at most at the 25 per cent level in the

[1] It should be kept in mind that these quoted values have been reduced by a factor of 0.8 in order to match the *WMAP* observations (Argüeso et al. 2003).

Table 1. Bispectrum values implied by residual accretion-flow sources. Column 1 details the frequency of observation, column 2 details the assumed flux limit, and columns 3 and 4 give bispectrum estimates for point-source Models A and B; column 5 are values reported from Argüeso et al. (2003) for standard radio/IR sources (Toffolatti et al. 1998).

ν (GHz)	S_{lim} (Jy)	b_{A}	b_{B}	b_{T}
30	1	7.0e−25	3.9e−26	6.4e−23
30	0.01	6.9e−28	3.9e−29	1.4e−26
30	0.001	1.9e−29	1.2e−30	n/a
44	1	1.2e−25	4.3e−27	7.2e−24
44	0.01	1.1e−28	4.3e−30	1.4e−27
44	0.001	3.1e−30	1.3e−31	n/a
100	1	3.2e−27	5.7e−29	9e−26
100	0.01	3.0e−30	5.7e−32	1.8e−29
100	0.001	7.5e−32	1.7e−33	n/a
350	1	4.5e−27	2.8e−29	7e−26
350	0.01	3.9e−30	2.8e−32	4.e−28
350	0.001	8.3e−32	8.4e−34	n/a

V band, and 2 per cent in the Q band. Given the *WMAP* bispectrum error bars, these numbers do not allows us to draw constraints on accretion-flow sources from these data. The current flux limit from *WMAP* is so high ($S_{\mathrm{lim}} \simeq 1$ Jy) that the contribution from these sources is subdominant with respect to what is inferred by more standard radio/IR sources. The observed bispectrum in the current *WMAP* data is consistent with a residual signal produced by the population of point sources observed at fluxes $S > 1$ Jy (Komatsu et al. 2003), which is not dominated by accretion-flow sources; rather, it is dominated by quasars and active galaxies as in the Toffolatti et al. (1998) model (see Fig. 2).

Because of the high sensitivity of *Planck*, point sources are expected to be detected down to a flux between 0.01 and 0.1 Jy. In Table 1 we show the contribution of accretion-flow sources to the *Planck* bispectrum. Their contribution at 100 GHz can be ∼15–20 per cent of the one from the Toffolatti et al. (1998) radio/IR point-source population as computed in Argüeso et al. (2003). In addition, *Planck* will observe over a broad frequency range, allowing a better description of point-source properties and possible discrimination between accretion-flow sources and other sources.

3.4 Future high-resolution SZ surveys

Future high-resolution SZ surveys in the 150–350 frequency range like ACT or APEX will allow to detect point sources down to a flux limit $S_{\mathrm{lim}} \simeq 1$ mJy. Because this point-source population presents an emission that extends to very high frequencies (see Fig. 1), it may give a significant contribution to the observed signal in future SZ surveys. Here we report the estimated pixel noise produced by residual sources for a different flux cut and for a fiducial pixel of 1 arcmin. Again, we report our results for the two models shown in Fig. 1. These two figures should roughly provide a lower and upper limit to the contribution coming from elliptical galaxies. Our results are summarized in Table 2 together with the estimates of White & Majumdar (2004) for the population of currently observed radio sources. For the sake of comparison, here we neglected the contribution of clustering. Accretion-flow sources may produce a noise that is ∼25–30 per cent of the one produced by the population of observed sources.

At the same frequencies, infrared sources are currently predicted to produce a slightly higher signal than radio sources (White &

Table 2. Pixel noise implied by residual accretion-flow sources in SZ experiments with 1-arcmin resolution. Columns 3 and 4 give predictions for Model A and B. Column 5 details predictions from White & Majumdar (2004) on the standard radio sources contribution (the two numbers refer to their two different extrapolations from low frequencies). The last three columns are in μK for a nominal 1-arcmin pixel.

ν (GHz)	$S_{\rm lim}(mJy)$	$\sigma_{b,\rm A}$	$\sigma_{b,\rm B}$	$\sigma_{b,r}$
150	1	1.3	0.3	5 (4)
150	5	2.2	0.5	9 (7)
150	10	2.8	0.6	12 (9)
150	50	2.9	0.9	20 (16)
220	1	1.1	0.3	4 (3)
220	5	2.0	0.4	7 (5)
220	10	2.5	0.5	9 (7)
220	50	2.6	0.7	16 (12)

Majumdar 2004). These IR estimates, however, may be biased high if part of the signal is due to lensing effect. Future experiments like the Submillimetre Common-User Bolometer Array 2 (SCUBA-2) and the *Herschel Space Observatory* will help in better characterizing the IR population.

4 CONCLUSIONS

We investigated the possible contribution to current and future CMB experiments from the accretion flows around supermassive BHs believed to harbour the centres of galaxies. These sources are typically faint and numerous, therefore they are likely to be observed as a residual signal in CMB experiments. A comparison with the number counts of *WMAP*-detected sources (and identified as elliptical galaxies) indicates that the bulk of the emission is probably higher than the $\sim 10^{28}$ erg s^{-1} Hz^{-1} assumed in our emission Model B.

We have showed that the residual signal produced by the emission from these unresolved sources could significantly contribute to the CBI and BIMA observed power spectrum. More specifically, these sources could make up to ∼40–50 per cent of the observed signal at $l > 2000$, therefore reducing the inferred value of $\sigma_8^{\rm SZ}$ by 6–7 per cent. As for all-sky experiments, we showed that the residual signal in the *WMAP* maps with the current flux limit is likely to be dominated by other kinds of sources, with accretion-flow sources contributing at the 2–3 per cent level at most.

Planck will have a better sensitivity than *WMAP* and will allow the detection of fainter sources, reducing the flux limit by at least a factor of 10 and possibly detecting hundreds of early-type galaxies. We showed that the residual signal from accretion-flow sources may contribute up to the 15 per cent to the bispectrum around 100 GHz. Unlike other radio sources, these sources typically show an inverted spectrum and are quite bright also in the infrared, up to about 300 GHz. This feature may facilitate their detection and discrimination with respect to the standard radio and infrared sources, especially with *Planck* that offers the potential of an all-sky experiment with a broad frequency coverage. A characterization of the *Planck* sources with the SDSS will allow the clear distinction between elliptical galaxies and other kinds of sources, allowing constraints to be put on accretion-flow models with radio number counts.

Future high-resolution CMB experiments like ACT and APEX operating in the 150–350 GHz range may also be affected by the emission from accretion flows in galaxies. The residual power spectrum is predicted to be about 25–30 per cent of the one expected for currently observed radio point sources. At these frequencies, however, IR sources are likely to be dominant, unless their number count is biased high due to lensing effects. Future surveys with instruments like SCUBA–2 and *Herschel* will help in clarifying this issue.

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REFERENCES

Argüeso F., González-Nuevo J., Toffolatti L., 2003, ApJ, 598, 86
Bennett C. L. et al., 2003, ApJS, 148, 97
Bernardi M. et al., 2003, AJ, 125, 1849
Blandford R. D., Begelman M. C., 1999, MNRAS, 303, L1
Bond J. R. et al., 2002, preprint (astro-ph/0205386)
Budavári T. et al., 2003, ApJ, 595, 59
Dawson K. S., Holzapfel W. L., Carlstrom J. E., Joy M., LaRoque S. J., Miller A. D., Nagai D., 2002, ApJ, 581, 86
De Zotti G., Granato G. L., Silva L., Maino D., Danese L., 2000, A&A, 354, 467
Di Matteo T., Quataert E., Allen S. W., Narayan R., Fabian A. C., 2000, MNRAS, 311, 507
Di Matteo T., Johnstone R. M., Allen S. W., Fabian A. C., 2001, ApJ, 550, 19
Gawiser E., Smoot G. F., 1997, ApJ, 480, L1
Guerra E. J., Haarsma D. B., Partridge R. B., 1998, BAAS, 30, 1307
Heymans C., Brown M., Heavens A., Meisenheimer K., Taylor A., Wolf C., 2004, MNRAS, 347, 895
Komatsu E., Seljak U., 2002, MNRAS, 336, 1256
Komatsu E. et al., 2003, ApJS, 148, 119
Lin H., Yee H. K. C., Carlberg R. G., Morris S. L., Sawicki M., Patton D. R., Wirth G., Shepherd C. W., 1999, ApJ, 518, 533
Magorrian J. et al., 1998, AJ, 115, 2285
Narayan R., Yi I., 1994, ApJ, 428, L13
Narayan R., Yi I., 1995a, ApJ, 444, 231
Narayan R., Yi I., 1995b, ApJ, 452, 710
O'Dea C. P., 1998, PASP, 110, 493
Perna R., Di Matteo T., 2000, ApJ, 542, 68
Pierpaoli E., 2003, ApJ, 589, 58
Pierpaoli E., Borgani S., Scott D., White M., 2003, MNRAS, 342, 163
Readhead A. C. S. et al., 2004, 609, 498
Rees M. J., Phinney E. S., Begelman M. C., Blandford R. D., 1982, Nat, 295, 17
Spergel D. N. et al., 2003, ApJS, 148, 175
Toffolatti L., Argueso Gomez F., de Zotti G., Mazzei P., Franceschini A., Danese L., Burigana C., 1998, MNRAS, 297, 117
Toffolatti L. et al., 1999, in de Oliveira-Costa A., Tegmark M., eds, ASP Conf. Ser. Vol. 181, Microwave Foregrounds. Astron. Soc. Pac., San Francisco, p. 153
Trushkin S., 2003, Bull. Spec. Astrophys. Obs., 55, 90
White M., Majumdar S., 2004, ApJ, 602, 565

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